CERTAIN ASPECTS OF RECENT SPECTROSCOPIC OBSERVATIONS OF THE GASEOUS NEBULÆ WHICH APPEAR TO ESTABLISH A RELATIONSHIP BETWEEN THEM AND THE STARS.

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The Lick Observatory has carried on during recent years a number of researches on the nebulæ. About two years ago these had taken a form sufficiently substantial to serve as the basis of a publication, and a number of memoirs entitled *Studies of the Nebulæ* were prepared at that time. Owing to industrial conditions developed by the war the printing of these papers was greatly delayed, and they have only now been issued as Volume XIII. of the *Publications of the Lick Observatory*. As one of the contributors to that work I have been asked to present some account of the investigation with which I am particularly concerned. It may be said that my own observtions are spectroscopic, and are confined to the gaseous nebulæ.

In attempting to give a comprehensive account of a survey in a relatively new field one is likely to be embarrassed by the heterogeneity of the material that presents itself for description. Astrophysics is essentially such a new field, and it is sometimes difficult to wander very far from what we consider, perhaps too confidently, the well-worked border without being overwhelmed with a diversity of new, and totally unexpected facts, which frequently serve to control the path of progress. Whatever was the original purpose of the quest, it is likely to have become modified by factors of its own development in such a way that the accumulated information bears apparently on a number of problems, and offers a complete solution of none of them. At any rate that has, in a sense, been the course of the present investigation. It had its beginnings in an attempt to measure the wave-lengths of the nebular lines somewhat more accurately than had been done before; in its present stage it is concerned chiefly with the distribution of the radiations through the nebulæ. There have been intermediate developments. The rather meager accumulation of material that is available is somewhat heterogeneous, and can hardly, in its entirety, be presented to an audience of general scientific interests. I shall, therefore, with a full sense of the limitations of the observations, undertake to consider them from the point of view of the relationship of the nebulæ to the stars. Such a relationship can be regarded as an element of the theory of stellar evolution, and it may be well to recall a few of the ideas that at present form the substance of that theory.

At the mention of the term "stellar evolution," in a general scientific gathering, one frequently becomes aware of an atmosphere of amused toleration, or tolerant skepticism. The raising of a brow, or the birth of an indulgent smile, diffuses such an atmosphere with the velocity of light. It is not my purpose to proselyte in the interests of any particular scientific creed, but inasmuch as we are approaching the observations from the point of view of stellar relationships, it may be well to recall the principal consideration that has led astronomers to the belief that such a thing as stellar evolution exists. The conception of stellar evolution finds its justification very largely in the principle of the conservation of energy. The sun and the stars are continually pouring out into space a simply inconceivable amount of energy in the form of radiation. We are all familiar with comparisons designed to help us sense the prodigious outflow. Perhaps as good a one as any is represented in the statement that if the surface of the earth, land and sea, were covered a mile deep with coal, the quantity of fuel represented would supply the output of solar heat for about a minute. Some of the stars radiate several thousand times as much heat as the sun. Whatever the nature of the process by which the energy is at present being replenished, it is impossible to conceive of the expenditure going on forever. Sooner or later the star must cool, and, through alteration in its temperature, suffer a change in its physical state. This process of change had been termed the evolution of the star.

On account of the enormous distances of the stars the principal means we have of studying their physical conditions is by spectroscopic analysis of their light, and we must therefore look to that to furnish the greater part of the material for whatever study can be made of the processes of stellar change.

Among the spectra of the heavenly bodies there is the greatest diversity; still, as Secchi first showed, they can nearly all be segregated into a comparatively few fairly homogeneous groups. While

FIG. 1.

the general validity of Secchi's classification is recognized , it is not sufficiently comprehensive nor exact to describe the great variety of spectra that have, in recent years, been made available for study through the aid of photography. The system referred to here will be that of the Draper classification, developed at the Harvard Col-

[1] The writer wishes to acknowledge his indebtedness for this illustration, excepting the first spectrum, to the Draper Catalogue (*Ann. H. C. O.*, 91), from which it is copied and where it serves as frontispiece to illustrate typical stellar spectra.

lege Observatory. The nature of the arrangement in that system is indicated by the typical spectra of the illustration (Fig. 1). The top spectrum is that of a Welf-Rayet star, or Class O star in the Draper system; following it is one of Class B, in which the dark lines of helium are strong. In the next the rhythmic hydrogen series predominates, while, as we go down, that in turn fades, and metallic lines, notably the strong calcium doublet, become pronounced. It will now be observed that while the sequence on the screen is based entirely on the occurrence of lines in the spectrum, another characteristic is shown as we pass from the top to the bottom of the picture, that is, the cutting off of the spectrum from the left side. This means the impoverishment of the violet end of the spectrum, as compared with the red. In other words we pass from stars that are bluish white, through those that are yellow to those that are red. It is one of the facts of our ordinary experience, fortified by elaborate theory and experiment, that this succession of color phenomena marks the cooling of an incandescent body; and the view has been generally adopted that exhibits such as that on the screen represent the spectra of stars in an order of continually decreasing temperature. Evidence confirmatory of this opinion is afforded by the fact that the spectral lines in the upper spectra are found in the laboratory to be characteristic of high temperature, while some of those in the lower are due to chemical compounds which can exist only in a comparatively cool environment.

Astronomers have, for a long time, thought that the spectral sequence here indicated offers the basis for inference with respect to stellar evolution, though there is not unanimity of opinion as to just how the evidence should be interpreted. It is manifestly impossible in the available time to indicate the many points of view from which the evidence has been considered. Probably a majority of those who are interested in such matters are inclined to interpret directly the sequence in the illustration, that is, to assume that the upper spectrum is one of the newly formed star, and that the following spectra are of stars in successive stages of development. This is equivalent to the hypothesis that a star originates at a high temperature and cools continuously throughout its period of visibility, fading out as a dim red object. This view is opposed by some others, chiefly by Sir Norman Lockyer, who regard it as out of harmony with the well-known laws of gaseous equilibrium. According to Lane's law a star, assuming it to be a gaseous mass, should grow hotter while contracting as the result of the loss of its heat.[2] This rise in temperature should continue until the material, through increased density, ceases to be a perfect gas, after which the temperature will fall. According to this conception a young star would be comparatively cool, and therefore, red; with increasing age it would grow hotter, achieve a maximum, and then cool off. There would be a succession of colors corresponding to temperature. Now all of the spectra of the red stars are not alike, nor are those of stars of the other groups, and in order to accommodate the spectral sequence to his hypothesis Lockyer has divided the red, yellow, and white stars into two groups which I shall for simplicity distingiush by means of subscripts. The red stars are the extremes of this system, the Red_1, according to Lockyer, being the youngest and the Red_2 the oldest of all the stars. Next to them come the corresponding groups of yellows and whites. I have attempted to diagram these two systems in a very elementary way by means of these curves (Fig. 2), in which time is measured from left to right, and temperature vertically. The hypothesis first referred to is represented in the figure on the left. Here we start with the hottest of all stars, those of the Wolf-Rayet or Class O group, and with falling temperature follow through the course of a star's life. The second hypothesis is outlined in the right-hand figure. These two diagrams are inadequate to represent all the views, and modifications of views that are held in one quarter or another. They

[2] It has been pointed out by Schuster (*Astrophysical Journal,* 17, 165, 1903) that Lane's law concerns itself with the temperature of the star's interior, while what we observe is the temperature at the surface. It is not certain that there is a simple relation between the two, since the surface temperature of a radiating body represents merely a balance between the rate of radiation and the rapidity with which heat can be supplied from the interior to make good the loss. If the transfer from within is effected mainly by convection the readiness with which it takes place will depend upon the force of gravity, that is to say upon the mass and dimensions of the star, as well as upon the temperature of its interior. It is therefore extremely doubtful to what extent the inferences from Lane's law should be expected to harmonize with the observations of the surface temperatures of stars, to which we are limited in our investigations.

are intended to represent only in the most general way the two classes or hypotheses which form part of the very speculative subject of stellar evolution, and are introduced to show at a glance the especial interest which attaches to the relationship of the nobulæ to one or the other of the stellar groups. It may be said with regard to the respective merits of the two hypotheses that the first has in its favor a pretty straightforward sequence of spectral similarities, with spectral evidence in the earlier groups of high temperature and intense electrical excitement, which fades through the spectra in the order indicated, while the second appears to receive support from

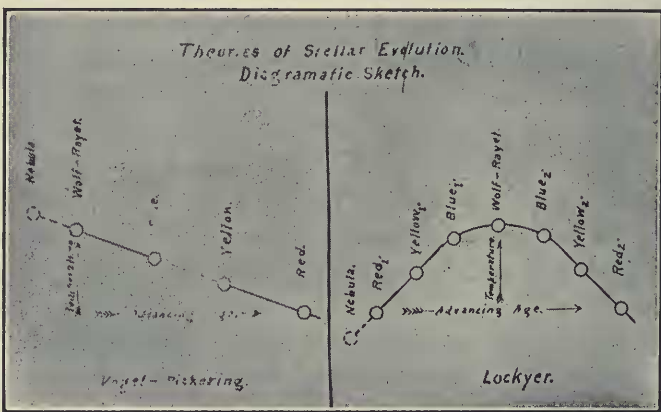

FIG. 2.

considerations of a general nature which indicate an exceptonally low density for some of the red stars.

It will be observed that both of these hypotheses assume the nebulæ as antecedent to the stars.

In searching for a nebular origin there are four general classes of objects among which it is necessary to distinguish: the spiral nebulæ, the extended amorphous nebulæ with continuous spectra, the extended gaseous nebulæ, and the small gaseous, or planetary nebulæ. With respect to the spirals, it is doubtful whether they belong to our stellar system, and in any event they are bodies of such stupendous size and mass that they can not be regarded as single stars in the process of formation. We know little of the second group, the extended white nebulæ.[3] The gaseous nebulæ, from their peculiar distribution along the Milky Way, are undoubtedly to be regarded as forming part of our system of stars, and in that sense furnish available material for our speculations. Furthermore they are the only ones whose spectra we are able to study with any degree of completeness, so that from the point of view of spectroscopy, our hope, for the present, must lie very largely with them. For these and other reasons it is between the stars and the gaseous nebulæ that a relationship has generally been sought. The connection has been claimed between the nebulæ and the Class O, or Wolf-Rayet stars, by those favoring one hypothesis on the basis of certain spectral similarities, and on the rather peculiar distribution of both groups of objects along the path of the Milky Way. The opposition, on the other hand, points to the occurrence of the bright lines of hydrogen in both the gaseous nebulæ and some of the red stars; and quite recently a number of the nebulium lines have been observed by Merrill at Mount Wilson to occur temporarily in the spectra of stars of that class. It will be seen that as between these two hypotheses, the matter of this connection with the nebulæ is one of vital concern. If the gaseous nebulæ can be shown to be related to the Wolf-Rayet stars the first hypothesis is strengthened, if, on the other hand, the connection is with the red stars the favor goes to the other theory. The relationship of the nebulæ to the one group or the other may then, in a sense, be regarded as a criterion to determine between these two conceptions as to the nature of stellar evolution.

I find it difficult in these remarks to be brief, and at the same time to avoid seeming to imply a degree of definiteness with respect to inferences that may be drawn from the evidence, and in fact, with respect to our conceptions of cosmogony, which would not be justified either by the available observational data nor by the present scientific point of view. I believe that astronomers, particularly observers, are, as a rule, not disposed to dogmatize on the subject

[3] These nebulæ like the gaseous or bright-line nebulæ favor the Milky Way, and are therefore to be regarded as members of our sidereal system, but our knowledge of their spectra is so limited that it does not afford a secure basis for speculation as to their physical constitution.

Fig. 3.

of stellar evolution, and there is an opinion, which I myself share, that we have not as yet sufficient evidence on which to found a secure conception of cosmogomy; still any fact is of scientific interest only in so far as it is related to others, and it is therefore necessary to examine all observational material from every reasonable point of view, and to appraise as well as possible its significance. It is for this reason that the present observations, in spite of their meagreness, are examined with respect to their bearing on our present notions of stellar evolution.

The gaseous nebulæ present a bright line spectrum such as is shown in the middle section of Fig. 3. The lines on the extreme right are the so-called first and second nebular lines. They are of unknown chemical origin. The third is due to hydrogen. The fourth strong line is the remarkable one at wave-length 4686 A, regarded, since the advent of the Bohr theory of the atom, as due to the recombination of completely ionized helium. It will, in these remarks, be referred to as the fourth nebular line. The upper spectrum is that of a red, the lower one of a Class O star. The red star has, like the nebula, narrow bright lines due to hydrogen and nebulium.[4] The Class O spectrum is composed of broad bright bands, a few of which correspond in position with the bright lines in the nebula. While having points in common, the three spectra are distinct. There has in past years been much discussion of their possible relationships, but until comparatively recently no certain connection had been established between either of the two outside spectra shown on the screen and the nebular spectrum in the center. The evidence which we have here to discuss is afforded by an examination of the nuclei or small star-like condensations in the planetary nebulæ. The investigation of these minute objects is somewhat exacting in its demands on the resources of observation, for the spectrum must be isolated from that of the rest of the nebula. When this is done they are found in many instances to exhibit the spectra of Class O stars. The diagram (Fig. 4) will indicate the method of making the observations. The sketch on the left represents the telescopic image

[4] The spectrum here shown is that of the variable R *Aquarii,* already mentioned as having been found by Merrill to exhibit, temporarily, the lines of nebulium.

of a star, assumed to be surrounded by envelopes of two kinds of gas, one larger than the other. The vertical parallels represent the slit of the spectroscope. To the right is the spectrum of the system showing bright gaseous lines, and the continuous spectrum of the star. The length of the bright lines is seen to offer a measure of the extent of the gaseous distribution. The objects are so faint that they can be observed only by photographs of long exposure, and in making these it is necessary to keep the nebula at precisely the

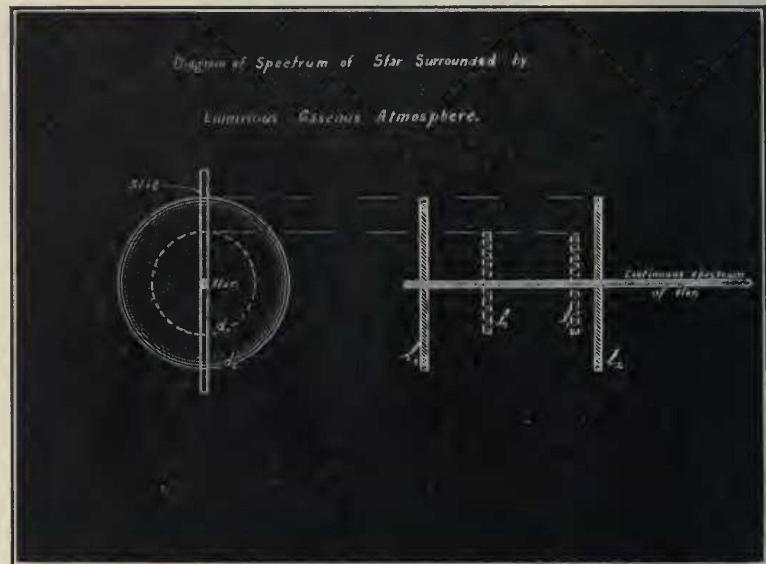

Fig. 4.

same position on the slit during the entire time, otherwise the record would be hopelessly confused. This is a tedious, and sometimes difficult task.

Turning now from the diagram to a real subject, Fig. 5 records the spectrum of the bright planetary in Andromeda. The fourth nebular line is shorter than the others, which indicates that the peculiar conditions that are favorable for its production obtain only comparatively close to the central star, in fact very largely within the inner area indicated in the preceding sketch. The spectrum of the nucleus is too faint to show well and is represented better in another

Fig. 5.

Fig. 6.

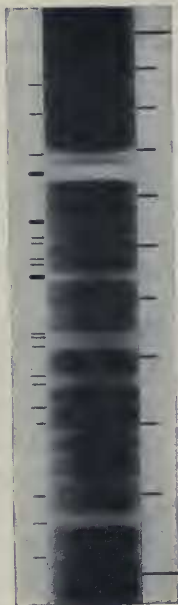

Fig. 7.

Fig. 8.

object (N. G. C. No. 40), which has a central condensation of exceptional strength, Fig. 6. The somewhat lumpy look of its continuous spectrum is due to the presence of emission bands. It will be noted that the positions of these bands do not correspond with those of the narrow nebular lines. It is a somewhat peculiar fact that the spectrum of a nebula and its nucleus differ markedly from each other. The photograph was made to show the narrow nebular lines, and the continuous spectrum is overexposed, but another record, Fig. 7, enlarged by means of a cylindrical lens, is more legible. The dots above the spectrum indicate the positions of the brighter emission bands of the Class O or Wolf-Rayet stars. The correspondence is complete, and the neucleus of the nebula is to be regarded as a star of that group. Fig. 8 shows the spectrum of another system of which the nucleus is extremely bright. The narrow lines belong to the nebula, while the hazy bands constitute the spectrum of the nucleus. The object was originally catalogued as a Class O star, and the surrounding nebulosity was found later. It is Campbell's so called *hydrogen envelope star,* in reality a planetary nebula.

Examples such as these might be multiplied, but there is no occasion for the repetition. Summarizing the results for all of the nebulæ observed, we have:

1. Of the forty-seven nebulæ examined thirty have nuclei sufficiently bright for their spectra to be photographed.

2. Of these thirty nuclei fifteen are Class O stars, and all show spectra indicative of high temperature.

I believe that upon this showing all of the nebular nuclei are to be regarded as belonging to the same general group as the Class O stars. When we recall that throughout the sky only one star in several thousand is known to belong to that group, it is difficult to escape the conclusion that there is an intimate connection between them and the nebulæ. The table summarises the argument in favor of such a connection; there are:

1. Nebulæ without nuclei.
2. Nebulæ with nuclei. The nuclei are in all instances stars of very high temperature, and in half of the cases show Class O bands.

3. Class O stars, with no (observed) nebulous surroundings. Temperature high.

In a single instance a star, previously described as belong to Class O, has been found to be surrounded by a planetary nebula, and it appears likely that other observations of a similar character will be made in the future, but such discoveries are hardly necessary to add to the proof of the connection. The only effect would be to remove one or more objects from group 3 and place them in group 2. In considering this relationship it should be borne in mind that the nebulæ and the Class O stars have comparatively few points of spectral correspondence, either in wave-length or in character of line, but the *nebular unclei* are Class O stars, and while their spectra differ from the spectra of their surrounding nebulosities, we have here the undoubted proof of *physical association* to bridge the gap in spectral similarity.

Reverting now to the hypothesis diagram of figure 2, this spectral relationship may be interpreted in various ways:

1. It may be taken as fortifying the hypothesis diagramed on the left and refuting the other.

2. The planetary nebulæ may be regarded as not standing in the prior relationship to the stars indicated in both diagrams, but as representing a development later in life.

3. They may be bodies exceptional character, not directly related to those in the supposed ordinary scheme of development.

While the evidence appears to favor the first there are arguments for and against all of these interpretations, but there is no occasion to discuss them here. If I have indicated at considerable length the possible bearing of the observations on present notions of stellar evolution it has been to point out the critical nature of nebular relationships rather than to attempt to bolster any particular theory. What is regarded as a definite outcome of the work is that it helps to perfect the proof of an element of stellar classification: the relationship of the planetary nebulæ to the Class O stars.

As bearing on the physical conditions obtaining in the planetary nebulæ which we find associated with these extremely hot, or electrically active stars, attention may be directed to a rather remarkable continuous spectrum which begins near the limit of the Balmer series of hydrogen and extends toward the ultra-violet. The spectrum may be seen in the photograph (Fig. 9) as a broad, faint band

Fig. 9.

lying to the left of the strong negular image.[5] A similar phenomenon has been observed by Evershed in the solar chromosphere. The spectrum is assumed to be due to hydrogen, though nothing of the sort has been found, with certainty, in the laboratory. It is perhaps significant that a spectrum would be expected there if we accept the Bohr atomic theory. From the atomic model which Bohr sets up, the Balmer line series of hydrogen develops from the recovery of a partially separated electron, while an extension of his equations to include the capture of free electrons by positive nuclei establishes a continuous spectrum at just this place. I must confess that I venture into the domain of the physicist with trepidation, and I have, for the purposes of this small excursion, sought the hospitable protection and guidance of Professor Millikan, which have been generously accorded. Professor Millikan has pointed out that the justification of this interpretation would depend upon the ratio of the energy of agitation of the electron to the energy expended in capture, that is to Planck's constant multiplied by the frequency of vibration at the limit of the Balmer series. A temperature of about 6000° centigrade would afford the requisite amount of kinetic energy. As a matter of fact that is about the temperature of the solar chromosphere, which, as we have seen, also emits this spectrum. It will be recalled in this connection that Buisson, Fabry, and Bourget have estimated the temperature of the Orion Nebula to be about 15000° Cent. It seems equally possible that the electronic

[5] This illustration, unlike the others, shows a spectrum recorded with a "slitless" spectograph. For this reason a bright line is represented by an image of the nebula, instead of by a narrow line, as in the other illustrations.

energy requisite for the production of this spectrum might be provided by an electric field. Interpreted through the medium of Bohr's very convenient, but equally myterious conception, this continuous spectrum indicates for the planetary nebulæ themselves a degree of temperature, or electrical excitation, comparable with that found to exist in their nuclei, and in other intensely radiating stars.